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Modeling Photoacoustic Efficiency during Erbium Laser Endodontics

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ABSTRACT

A simple phenomenological model of the efficiency of photoacoustic transients encountered in Erbium laser endodontics is presented. The model provides a relationship between the optodynamic energy conversion efficiency and the laser pulse duration and energy that can be used to optimize laser endodontics protocols. The mechanical energy of the laser-generated vapor bubbles within the endodontic irrigant is found to be proportional to the square of the laser pulse energy, and is inversely proportional to the cube of the thickness of the thermally affected layer of the endodontic irrigant. With conical tips, the optodynamic (OD) energy conversion efficiency is five times higher in comparison to when flat tips are used.

It is demonstrated that the critical parameter for achieving efficient debridement of root canal systems is the Erbium laser pulse duration. Based on the phenomenological model, laser endodontics with an Er:YAG (SSP mode) laser will produce at least a three-times-higher energy of photoacoustic transients within a root canal system than an Er,Cr:YSGG laser (H mode) with the same pulse energy.

Key words: Er:YAG; Er,Cr:YSGG, laser dentistry, optoacoustics, endodontics, PIPS, optodynamics.

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I. INTRODUCTION

There are many medical treatments in different areas of dentistry, such as endodontics, periodontics, implantology, or bone surgery where an effective irrigation, including debriding, cleaning and decontamination of the anatomical cavities is needed [1-5].

For example, a goal of endodontic treatment is typically to obtain an effective cleaning and decontamination of the root canal system (e.g., removal of bacteria and other contaminants from the smear layer) [6]. Clinically, traditional endodontic techniques use mechanical instruments as well as ultrasound and chemical irrigation in an attempt to shape, clean and completely decontaminate the endodontic system [7-9].

The complexity of the root canal system is well known. Numerous lateral canals (with various dimensions and with multiple morphologies) branch off from the principal canals [10-12]. The effectiveness of debriding, cleaning and decontaminating in the intra-radicular space is often limited, given the anatomical complexity and the inability of common irrigants to penetrate into the lateral canals and/or the apical ramifications. For these reasons, effectively debriding, cleaning and decontaminating the root system thus represents a challenge [13, 14].

Accordingly, improved methods, techniques and technologies that can improve irrigation, including cleaning, debriding and disinfection of anatomical cavities (e.g., root canal systems, periodontal pockets, surgical holes and the like) are desirable [15].

The use of lasers has been studied in endodontics since the early 1970s [16-18], and lasers are now widely used in dental applications [19-25]. Early attempts at laser use in endodontics typically resulted in occlusion of dentinal tubules, thereby undesirably decreasing their permeability. Some early reports indicated a reduction of bacterial load, although in connection with unwanted generation of heat [23, 24]. More recent investigations have focused on laser-activated irrigation approaches that produce explosive vapor bubbles with acoustic transient effects, facilitating removal of debris from intricate tooth anatomy [26-27]. These approaches permit fluid interchange and the removal of organic tissue and microbes, resulting in disinfection of the dentinal tubules [28].

Recent studies have reported how the use of an Er:YAG laser, equipped with a special fiber tip, in combination with 17% EDTA solution, using a very low pulse duration (50 microseconds) and low energy

(20 mJ) resulted in effective debris and smear layer removal with minimal or no thermal damage to the organic dentinal structure (through a photoacoustic technique called Photon Induced Photoacoustic Streaming or "PIPS™") [29, 30]. Also the same PIPS™ protocol in combination with 6% sodium hypochlorite solution has been investigated and shown to three-dimensionally reduce the bacterial load and its associated biofilm in the root canal system [31, 32].

The dynamics of photoacoustic transients is a complex process. The bubble dynamics and the optodynamic (OD) energy conversion efficiency have been studied experimentally [33-35], however, exact theoretical modeling is lacking. In this paper, a simple phenomenological model is presented, based on experimental data, which describes the relationship between the optodynamic energy conversion efficiency and laser parameters such as laser pulse duration and energy.

II. MATERIALS AND METHODS

During the laser irrigation procedure, the interaction of a pulsed laser beam with the irrigant results in rinsing, irrigating and disinfecting of the pulp chamber and root canal to provide substantially clean and pulp-free dentinal walls lining the chamber and root canal, ready for subsequent filling. The laser beam is delivered by means of a laser handpiece to a fiber tip, which is immersed into a liquid introduced into the open area of a pulp chamber to provide a liquid reservoir (See Fig. 1a). The liquid may consist of water or antibacterial and/or tissue dissolution irrigants such as NaOCl or EDTA, which, in combination with Photon Induced Photoacoustic Streaming, have proven to be very efficient in biofilm removal [31, 32].

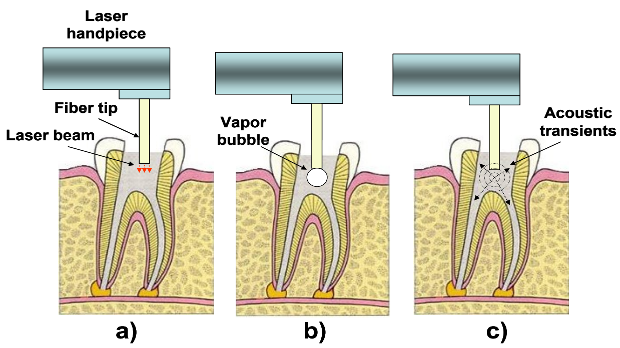

Fig. 1: Laser irrigation procedure: a) A pulsed laser beam is delivered to the pulp chamber through a fiber tip immersed into a liquid irrigant; b) Rapid vapor bubble expansion occurs through laser-driven heating and evaporation of the liquid; c) Strong acoustic transients and shock waves develop when the bubble collapses after the end of the laser pulse.

When a pulsed laser beam that is highly absorbed in liquids – either in a linear or non-linear regime – is delivered to such a liquid, bubble generation occurs (Fig. 1b). In this paper, only the linear absorption regime is considered. This regime applies when the laser pulse power density in a liquid is not high enough to result in ionization or other non-linear interactions with water molecules. Typically, lasers with pulse durations in the microsecond or millisecond range, such as flash-lamp pumped free-generation Erbium lasers, operate in a linear regime. Examples of Erbium lasers are the Er:YAG (λ= 2.94 μm) and Er,Cr:YSGG (λ= 2.73 μm) laser [36 - 38].

For free generation Erbium laser pulse durations there are no shock waves created in the liquid during the bubble expansion [35]. Instead, the energy stored in the bubble is converted into acoustic energy only after the bubble reaches its maximum size, and the difference in pressures forces the bubble to collapse (Fig. 1c). As a result, the bubble's energy (E_B) which can be used for debriding, cleaning and disinfecting the root system, is proportional to the volume of the bubble (V_B) at its maximum size (V_{max}). The bubble's energy E_B can be mathematically calculated from

$$E_B = p \times V_{max} \tag{1}$$

where p equals the hydrostatic pressure of the liquid, and equals 0.1 J/cm³ [35]. The optodynamic efficiency of the conversion of the laser pulse energy (E_L) into the energy of acoustic transients can therefore be written as [35]:

$$\eta = \frac{E_B}{E_L} = p \times \frac{V_{max}}{E_L} \tag{2}$$

It is important to note that a laser energy threshold exists below which no vapor bubble is generated. The analysis is especially simple if the laser pulse is so short that heat diffusion effects during the laser pulse can be neglected. The evaporation threshold laser fluence F_{th} (in J/cm²) is then [39]:

$$F_{th} = \frac{h_e}{\mu} \tag{3}$$

where h_e marks the specific heat for evaporation, and μ is the absorption coefficient of a particular laser wavelength in the liquid irrigant. Equation 3 states that the minimal volume that has to be evaporated in order to create a bubble is the volume of the liquid within the laser penetration length, $1/\mu$.

By assuming the liquid to be water and taking into account that the liquid needs to be first heated up to the boiling temperature and then evaporated, the specific heat for the evaporation of water is approximately 3×10^3 J/cm^3.

Since the laser fluence threshold depends inversely on the absorption coefficient μ, laser wavelengths with high absorption coefficients in the irrigant are more suitable for laser activation. Here, the Er:YAG laser wavelength (2.94 μm) is at an advantage since of all laser wavelengths it has the highest absorption coefficient in water (μ = 1200 cm^{-1}) and other OH- containing liquids, and thus exhibits the lowest threshold for laser activation. For example, laser fluence thresholds for Er,Cr:YSGG (2.73 μm), Nd:YAP (1.34 μm) and Nd:YAG (1.064 μm) laser wavelengths are respectively approximately 3×, 1,000× and 10,000× higher as compared to that of Er:YAG.

For longer pulse durations, the evaporation threshold is expected to increase because of the conductive loss of heat from the interaction layer. The characteristic diffusion depth x_d to which the liquid temperature is affected during the duration of a laser pulse t_p can be estimated by:

$$x_d = (4Dt_p)^{\frac{1}{2}} \tag{4}$$

where D is the thermal diffusivity of the liquid [11]. The thermal diffusivity of water is D = 1.4×10^3 J/cm^3.

The characteristic value that separates the diffusion and no-diffusion regimes can be estimated by equating the diffusion length with the laser penetration depth 1/μ, to obtain the thermal relaxation time:

$$\tau = (4D\mu^2) \tag{5}$$

With water as a liquid, for free generation Er:YAG and Er,Cr:YSGG lasers (with typical pulse durations in the range of t_p = 30 - 1500 μs), Eq. 5 yields approximately τ = 1 μs and τ = 11 μs, respectively. Since the thermal relaxation times are shorter than typical Erbium laser pulse durations, this indicates that Erbium lasers operate in the thermal diffusion regime and that the efficiency of irrigation will depend strongly on the pulse duration. As an example, for a pulse duration of t_p = 300 μs, Eq. 4 yields x_d = 13 μm, which is much longer than the penetration depth of Er:YAG (1/μ = 0.8 μm) or Er,Cr:YSGG (1/μ = 2.4 μm) lasers. Therefore, when comparing Er:YAG and Er,Cr:YSGG lasers, the difference in their wavelengths will have less influence on their respective optodynamic (OD) energy-conversion efficiencies than any difference in their pulse durations.

The dynamics of vapor bubble formation and collapse is a complex process, and exact theoretical modeling is lacking. However, the bubble dynamics and the OD energy conversion efficiency have been studied experimentally for the case of an Er:YAG laser source with water as an irrigant [35]. The study by Gregorcic et al. [35] showed the OD energy conversion efficiency to increase approximately linearly with laser pulse energy and to decrease rapidly with increasing pulse duration t_p, as expected when laser interaction with liquid occurs in a thermal diffusion regime. Measurements were performed with two types of fiber tips, with either a flat or a conical ending. The diameter d, of both types of the tips was d = 400 μm, and the length of the conical ending was 830 μm. The cross area S of the fiber tip was S = $\pi d^2/4$ = 1.26 x E^{-3} cm^2. The bubble's shape and the OD energy conversion efficiency depended on the fiber tip geometry. A spherical bubble developed when the conical fiber tip was used, while a cylindrical, channel-like bubble was obtained with the flat fiber tip.

Experimental results, as obtained from Figs. 11 and 12 presented in Gregorcic et al. [35], formed the basis for the present study and are shown in Fig. 2.

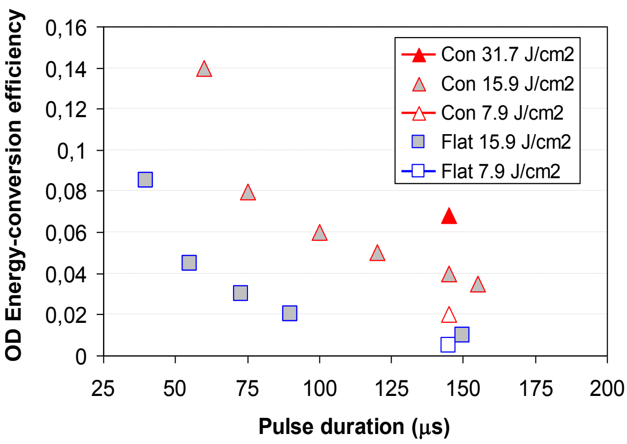

Fig. 2: Measured OD energy-conversion efficiency η, as a function of laser pulse duration and laser pulse fluence F (in J/cm^2), for a conical and flat fiber tip with a diameter of 400 μm. The data is taken from Gregorcic et al. [35].

In this work, we set out to obtain a simple phenomenological expression which would describe the above experimentally observed dependence of η on laser pulse duration t_p and laser pulse fluence F = E_L/S.

III. RESULTS

By numerically fitting curves to the experimental data shown in Fig. 2, it was found that the data can be fitted rather well within a broad range of parameters by the following phenomenological expression:

$$\eta = \frac{K_e \times \left(\frac{E_L}{S}\right)}{{t_p}^{3/2}} = \frac{K_e \times F}{{t_p}^{3/2}} \qquad (6)$$

where the efficiency proportionality factor K_e is equal to K_{ef} = 1.26 μs$^{3/2}$ J^{-1} cm^2 for the flat fiber, and K_{ec} = 3.78 μs$^{3/2}$ J^{-1} cm^2 for the conically ended fiber.

The experimental data from Gregorcic et al. [35], together with the corresponding phenomenological model, are shown in Fig. 3.

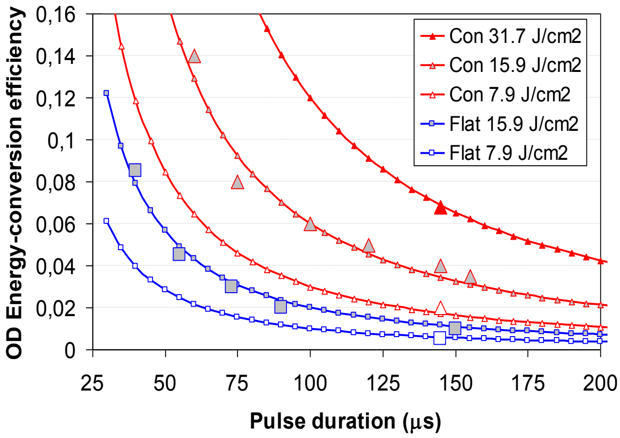

Fig. 3: Phenomenological model (small symbols) and the experimental data (large symbols) for OD energy-conversion efficiency. The experimental data is from Gregorcic et al. [35].

As can be seen from Fig. 3, the OD energy-conversion efficiency can be modeled phenomenologically with satisfactory results.

It should be noted that the above efficiency proportionality factors strictly apply only to the fiber tip diameter used by Gregorcic et al. [35]. However, assuming that the OD energy-conversion efficiency depends primarily on the bubble's shape, then Eq. 6 can be used also for other fiber tip diameters. Experiments show that as the diameter of a flat fiber tip is reduced, the bubble has a progressively more spherical shape. Therefore, for $d \rightarrow 0$, $K_{ef} \rightarrow K_{ec}$.

IV. DISCUSSION

A benefit of the phenomenological model (Eqs. 7 and 8) is that it provides an estimate for the OD energy-conversion efficiency for different laser pulse energy durations and sources without having to perform demanding experimental studies. As an example, Fig. 4 shows the predicted values for η over a broad range of pulse durations and fluences.

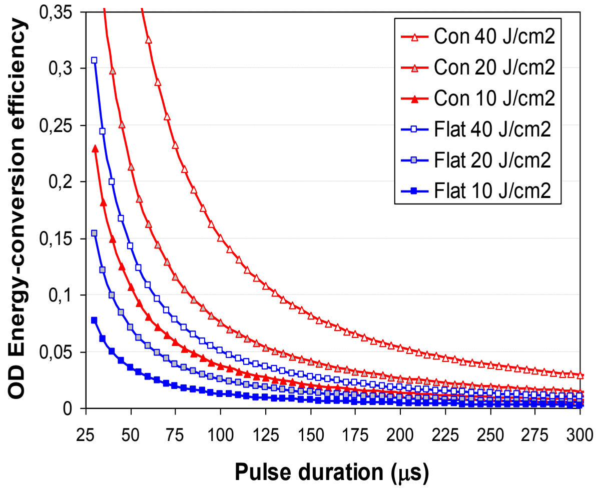

Fig. 4: Dependence of the OD energy-conversion efficiency on laser pulse duration and fluence, as given by the phenomenological model.

Using Equations 6 and 2, we obtain the following dependence of the maximal bubble volume of the laser pulse fluence (F), pulse duration (t_p) and fiber tip cross area (S):

$$V_{max} = \eta \times \frac{E_L}{p} = K_V \times S \times \frac{F^2}{{t_p}^{3/2}} \qquad (7)$$

where the bubble's volume proportionality factor K_v is equal to K_{vf} = 12.6 μs$^{3/2}$ J^{-2} cm^5 for the flat fiber, and K_{vc} = 37.8 μs$^{3/2}$ J^{-2} cm^5 for the conically ended fiber.

A comparison of the calculated maximal volume using Eq. 7, and the experimental data shows a good agreement of the model with the experiment (See Fig. 5).

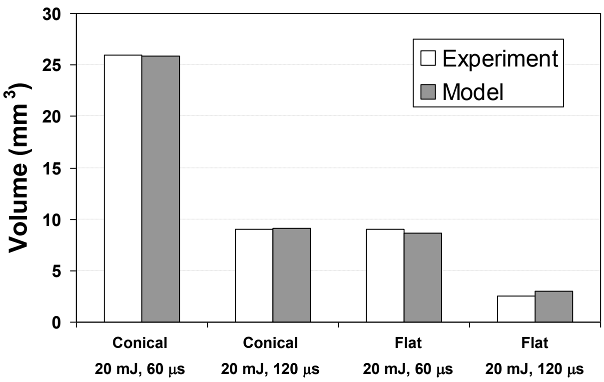

Fig. 5: Comparison of the values for the maximal bubble volume (V_{max}) for the fiber tip diameter d = 400 μm, as obtained experimentally and with the phenomenological model. The experimental data is from Gregorcic et al. [35].

It is interesting to explore what stands behind the phenomenological Eq. 6. By noting that the diffusion length x_d is proportional to $t_p^{1/2}$ (See Eq. 4), we obtain

$$E_B \propto \frac{{E_L}^2}{{t_p}^{3/2}} \propto \frac{{E_L}^2}{{x_d}^3} \quad (8)$$

The mechanical energy E_B, of the acoustic transients is proportional to the square of the laser pulse energy and is inversely proportional to the cube of the thermal diffusion length.

It is important to note that even though the phenomenological expression in Eq. 6 was obtained by fitting Er:YAG experimental data, the expression applies also to other highly absorbed free-generation lasers which operate in a thermal diffusion regime. As was shown above, both free-generation Erbium lasers, Er:YAG (2.94 μm) and Er,Cr:YSGG (2.73 μm), have their optical penetration depths shorter than the thermal diffusion depths for pulse durations above 11 μs. Therefore, they both operate in the thermal diffusion regime, and Eq. 6 applies equally well to both of them. On the other hand, Eq. 6 would not be directly suitable, for example, with the Nd:YAP (1.34 μm) laser since its optical penetration depth of 1000 μm is much longer than the thermal diffusion depth.

Erbium lasers, Er:YAG and Er,Cr:YSGG, differ not only in their wavelength, but also in their range of available pulse duration modes. Typically, for the same flashlamp pump pulse duration, the output laser pulse duration is longer for the Er,Cr:YSGG laser. This is due to the long pulse decay tail exhibited by the Er,Cr:YSGG laser [37]. The long decay tail is a consequence of the slow internal ion-ion up-conversion process which continues to "pump" the Er,Cr:YSGG laser also after the flashlamp pump pulse has already ended.

Recently, pulse shapes and durations of two commercially available Erbium laser systems (LightWalker Er:YAG laser in SSP pulse duration mode, and iPlus Er,Cr:YSGG laser in H duration mode) were measured for the same laser pulse energy of 20 mJ [36]. Figure 6 shows the temporal development of the cumulative output laser energy during the SSP and H pulses for both laser types.

As can be seen from Fig. 6, the pulse shape and duration of the SSP and H laser pulses are for E_L= 20 mJ such that 95% of the pulse energy is delivered to the treatment area within approximately the first 40 μs of the Er:YAG pulse, and within approximately the first 300 μs of the Er,Cr:YSGG pulse.

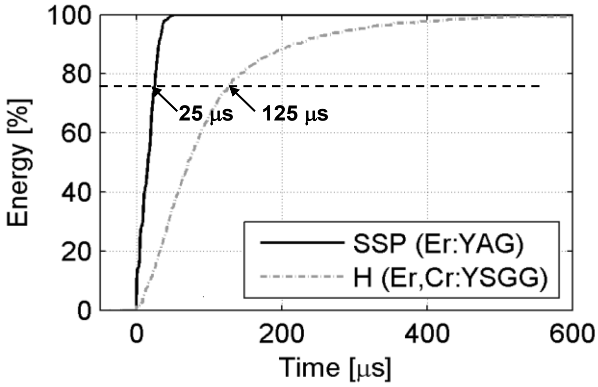

Fig. 6: Measured temporal development of the cumulative output laser energy for Er:YAG (SSP mode; LightWalker AT) and Er,Cr:YSGG (H mode; WaterLase iPlus). Temporal developments are shown for the same laser pulse energy of 20 mJ. Data is from Diaci et al. [36].

By taking pulse durations of $t_{p(75\%)}$ = 25 μs for the Er:YAG laser source and $t_{p(75\%)}$ = 125 μs for the Er,Cr:YSGG laser source and using the phenomenological model, we obtain the OD energy-conversion efficiencies for both laser sources as shown in Table 1.

Table 1: Calculated OD energy-conversion efficiency η, as obtained from Eq. 6 for the conically ended fiber with a diameter of 400 μm.

	Er:YAG	Er,Cr:YSGG
E_L	20 mJ	20 mJ
D	400 μm	400 μm
T_p	25 μs	125 μs
η	**0.48**	**0.04**

Because of the difference in the pulse durations, the OD energy-conversion efficiency η, of the H mode Er,Cr:YSGG lasers is 0.46/0.04 = 11 times smaller than that of the SSP mode Er:YAG laser. Since the energy of the laser generated vapor bubbles is found to be proportional to the square of the laser pulse energy, it can be concluded from Table 1 above, that the H mode Er,Cr:YSGG laser requires at least $\sqrt{0.46/0.04} = 3.3$ times higher laser energy than the SSP mode Er:YAG laser in order to generate acoustic transients with the same mechanical energy. Note that in the above it was not taken into account that the pulse duration of the Er,Cr:YSGG laser will increase somewhat when the energy is increased three-fold, and that the resulting further decrease in η would have to be compensated by a further increase in laser energy.

The above difference in OD energy conversion efficiency is observed also in clinical practice. Typical Erbium laser endodontics protocols require 15 mJ of energy (PIPS™ protocol) when the SSP mode Er:YAG laser is used [40], and 40-60 mJ (LAI protocol) when the H mode Er,Cr:YSGG laser is used [41]. When increasing the energy, the endodontist has always to consider the dentinal ablation threshold of $F \approx 6\ J/cm^2$ [39]. This threshold can be easily reached when using fiber tips with small diameters. For a 400 μm fiber tip, and with the fiber tip in contact with the dentinal wall, the dentinal ablation threshold is reached with laser energies of about 10 mJ. During root canal therapy the apical foramen can be easily penetrated, followed by extrusion of used irrigants in the periapical bone tissue. This may potentially cause damage, such as: post-operative pain, flare-ups and even failure in the lesion repair [42].

V. CONCLUSION

A simple phenomenological model of the efficiency of photoacoustic transients encountered in Erbium laser endodontics is presented. The model provides a relationship between the optodynamic energy conversion efficiency and the laser pulse duration and fluence that can be used to optimize laser endodontics protocols. With conical tips, the OD energy conversion efficiency is three times higher in comparison to when flat tips are used.

It is demonstrated that the critical parameter for achieving efficient debridement of root canal systems with Erbium lasers is the laser pulse duration. The energy conversion efficiency is found to be inversely proportional to the cube of the thickness of the thermally affected layer of the endodontic irrigant. Similarly, the mechanical energy of the acoustic transients is proportional to the square of the laser pulse energy and is inversely proportional to the cube of the thermal diffusion length.

Based on the phenomenological model, the H mode Er,Cr:YSGG laser requires at least three-times-higher laser energy than the SSP mode Er:YAG laser in order to generate acoustic transients with the same mechanical energy. It is important to note that this prediction of the theoretical model still needs to be confirmed experimentally.

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